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A NUMERICAL METHOD FOR PREDICTION  
OF THE 1000 MILLIBAR SURFACE

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A NUMERICAL METHOD FOR PREDICTION OF  
THE 1000 MILLIBAR SURFACE

by

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## ABSTRACT

The development of a numerical 1000-mb prognosis by means of a 500 to 1000-mb thickness forecast is investigated. The thickness forecast is based, in part, on the 500-mb barotropic prognosis as developed by Fleet Numerical Weather Facility, Monterey.

Forecasts were prepared for three days during May 1966, with various amounts of smoothing of the component fields. The model showed promise of producing a rapid, usable prognosis; however further testing is needed with the probable addition of some climatic constraints. It is also hoped that the yet untried diabatic heating and surface friction terms will provide some further improvement.

TABLE OF CONTENTS

Section	Page
1. Introduction	11
2. Development of the Prognostic Model	12
3. Development of the Heating Term	16
4. Development of the Terrain and Friction Terms	21
5. Programming the Prognostic Equations for the Control Data 1604 Computer	22
6. Results and Conclusions	26
7. Acknowledgements	29
8. Bibliography	30





## LIST OF ILLUSTRATIONS

Figure		Page
1.	Two Layer Division of the Atmosphere between 1000-mb and 500-mb	31
2.	Plot of Bowen Ratio vs Sea-Air Temperature Difference	32
3.	500-1000 mb Thickness Analysis 00Z 20 May 1966	33
4.	24-Hour Thickness Prognosis from 00Z 20 May 1966	34
5.	24-Hour Thickness Prognosis from 00Z 20 May 1966 (Decreased Smoothing)	35
6.	500-1000 mb Thickness Analysis 00Z 21 May 1966	36
7.	1000-mb Height Analysis 00Z 20 May 1966	37
8.	24-Hour 1000-mb Height Prognosis from 00Z 20 May 1966	38
9.	500-1000 mb Thickness Analysis 12Z 23 May 1966	39
10.	24-Hour Thickness Prognosis from 12Z 23 May 1966	40
11.	500-1000 mb Thickness Analysis 12Z 24 May 1966	41
12.	1000-mb Height Analysis 12Z 23 May 1966	42
13.	24-Hour 1000-mb Height Prognosis from 12Z 23 May 1966	43
14.	500-1000 mb Thickness Analysis 12Z 29 May 1966	44
15.	24-Hour Thickness Prognosis from 12Z 29 May 1966	45

16.	FNWF 24-Hour Thickness Prognosis from 12Z 29 May 1966	46
17.	500-1000 mb Thickness Analysis 12Z 30 May 1966	47
18.	1000-mb Height Analysis 12Z 29 May 1966	48
19.	24-Hour 1000-mb Height Prognosis from 12Z 29 May 1966	49
20.	FNWF 24-Hour 1000-mb Height Analysis from 12Z 29 May 1966	50
21.	1000-mb Height Analysis 12Z 30 May 1966	51

# TABLE OF SYMBOLS AND ABBREVIATIONS

$c_p$	Specific heat of dry air at constant pressure
$c_v$	Specific heat of dry air at constant volume
$\nabla$	Two dimensional del operator on constant pressure surface
$f$	Coriolis parameter
FNWF	Fleet Numerical Weather Facility, Monterey, California
$g$	Acceleration of gravity
$h$	Thickness of layer 1000 mb to 500 mb
$h_1$	Thickness of layer 750 to 500 mb
$h_2$	Thickness of layer 1000 mb to 500 mb
$J$	Jacobian
$L$	Latent heat of evaporation
mb	millibar
$\zeta$	Absolute vorticity
$p$	Pressure
$\varphi$	Latitude (degrees)
$Q$	Change of thickness due to diabatic heating
$\dot{Q}$	Heating rate
$Q_f$	Flux of heat through air/ocean interface
$R$	Gas constant per gram of dry air
RMSE	Root-mean-square error
$\rho$	Density
$t$	Time

$T$	Temperature ( $^{\circ}\text{K}$ )
$T_a$	Temperature of air at the surface
$\mathbf{V}$	Vector wind
$w$	Vertical velocity
$w_t$	Terrain induced vertical velocity
$z$	Height of constant pressure surface
$\zeta$	Relative vorticity

## SUBSCRIPTS

a	air at surface
Y	previous estimate
gs	geostrophic
gs10	1000-mb geostrophic
s	sea surface
t	terrain
5	500-mb
6	625-mb
7	750-mb
8	875-mb
10	1000-mb



## 1. Introduction

With the development of the high speed digital computer, the problem of weather prognosis has evolved from one of qualitative reasoning by an experienced forecaster to one of objective computations based on mathematical equations representing the motions of the atmosphere. At this time, daily numerical analysis and prognostic charts are being produced at Fleet Numerical Weather Facility, Monterey (FNWF), and rapidly disseminated to fleet units around the world. The entire field of meteorology is in a rapid state of change with more and more products being produced numerically.

The most successful numerical prognosis has been at the 500 mb level. If a successful numerical isobaric thickness forecast could be developed, the success of the 500-mb forecast could then be reflected to higher and lower levels. The objective of this research is to obtain a dependable 24-hour numerical forecast of thickness for the layer between 500-mb and 1000-mb, and then using FNWF's 500-mb barotropic forecast obtain a 1000-mb height prognosis.

The thickness of an air layer at any given time and place is dependent upon the mean temperature of the air column. If we look at thickness change as a result of the advection of thickness lines only, it appears that there is no heat loss or gain as the air moves across the surface of the earth nor are there vertical motions. This is not true, of course, since the air gains or loses heat through



radiative, dynamical, and conductive processes, and through latent heat exchange resulting from phase changes of the water constituent.

In the model used in this study, in addition to advection, an empirical heating term is developed to account for heating or cooling by evaporation or condensation and for turbulent transfer of sensible heat over ocean surfaces.

To account for the dynamic processes, vertical velocity is assumed to be a second order function of pressure. The 1000-mb vertical velocity is composed of a terrain upslope term and a friction term. Heat gained or lost by radiative processes was ignored as negligible over the 24-hour period.

## 2. Development of the Prognostic Model

A two layer model is used in the development of the prognostic equations. The lower troposphere is divided into two layers as illustrated in Fig. 1.

By use of the equation of state and the hydrostatic equation, the thermodynamic equation may be reduced to the following form

$$\frac{\partial}{\partial t} \left( \frac{\partial z}{\partial p} \right) + \mathbf{V} \cdot \nabla \frac{\partial z}{\partial p} + \omega \left( \frac{c_v}{c_p p} \frac{\partial z}{\partial p} + \frac{\partial^2 z}{\partial p^2} \right) = - \frac{R \dot{Q}}{g c_p p} \quad (1)$$

Replacing the vertical derivatives above by finite difference and simplifying leads to

$$\frac{\partial h}{\partial t} + \mathbf{V} \cdot \nabla h + \omega \left( \frac{c_v}{c_p p} h - \frac{(h_1 - h_2)}{\Delta p} \right) = \frac{R \Delta p}{g c_p p} \dot{Q} \quad (2)$$



Where  $\Delta z = h$ , the thickness.

In the layer 1000 to 500 mb it has been noted that  $\omega$  can generally be approximated by a second order equation in pressure.

$$\omega = a(x,y,t) \left( \frac{p_0 - p}{p} \right)^2 + b(x,y,t) \left( \frac{p_0 - p}{p} \right) + \omega_{10} \quad (3)$$

By means of equation (2) it may be shown that

$$\omega_6 = \frac{9}{16} a + \frac{3}{4} b + \omega_{10} \quad (4)$$

$$\omega_8 = \frac{1}{16} a + \frac{1}{4} b + \omega_{10} \quad (5)$$

$$\left( \frac{\partial \omega}{\partial p} \right)_5 = -\frac{2a}{p_5} - \frac{b}{p_5}, \quad \left( \frac{\partial \omega}{\partial p} \right)_{10} = -\frac{b}{p_5} \quad (6)$$

Taking the vorticity equation at 500 mb in the form

$$\frac{\partial \zeta}{\partial t} + \mathbf{V}_5 \cdot \nabla \eta_5 = \eta_5 \left( \frac{\partial \omega}{\partial p} \right)_5$$

and substituting from equation (6) gives

$$b = -2a - \frac{p_5}{\eta_5} \left( \frac{\partial \zeta}{\partial t} + \mathbf{V}_5 \cdot \nabla \eta_5 \right) \quad (7)$$

Equation (2) is now evaluated for layer 2 giving

$$\frac{\partial h_2}{\partial t} + \mathbf{V}_8 \cdot \nabla h_2 + \omega_8 \left( \frac{c_v}{c_p p_8} h_2 - \frac{(h_1 - h_2)}{\Delta p} \right) = \frac{R \Delta p}{g c_p p_8} \dot{Q}_2$$

The above equation may be written

$$\omega_8 = \frac{1}{\sigma_2} \left( \frac{R \Delta p}{g c_p p_8} \dot{Q}_2 - \frac{\partial h_2}{\partial t} - \mathbf{V}_8 \cdot \nabla h_2 \right) \quad (8)$$

Where

$$\sigma_2 = \left( \frac{c_v}{c_p} p_8 h_2 - \left( \frac{h_1 - h_2}{\Delta p} \right) \right)$$

Combining equations (5) and (8) and simplifying leads to

$$a = -\frac{16}{7} \left[ \frac{1}{\sigma_2} \left( \frac{R \Delta p}{g c_p p_8} \dot{Q}_2 - \frac{\partial h_2}{\partial t} - \mathbf{V}_8 \cdot \nabla h_2 \right) - \omega_{10} \right] - \frac{4}{7} \frac{p_8}{\eta_5} \left( \frac{\partial \zeta}{\partial t} + \mathbf{V}_5 \cdot \nabla \eta_5 \right) \quad (9)$$

With the geostrophic assumption for relative vorticity

$$\frac{\partial \zeta}{\partial t} = g/f \nabla^2 \frac{\partial \zeta}{\partial t}$$

it follows that

$$g/f \nabla^2 \frac{\partial \zeta}{\partial t} = -\mathbf{V}_7 \cdot \nabla \eta_7 + \eta_7 \left( \frac{\partial \omega}{\partial p} \right)_7 \quad (10)$$

$$g/f \nabla^2 \frac{\partial \zeta}{\partial t} = -\mathbf{V}_{10} \cdot \nabla \eta_{10} + \eta_{10} \left( \frac{\partial \omega}{\partial p} \right)_{10} \quad (11)$$

Subtracting equation (11) from (10) yields

$$g/f \nabla^2 \frac{\partial h_2}{\partial t} = \mathbf{V}_{10} \cdot \nabla \eta_{10} - \mathbf{V}_7 \cdot \nabla \eta_7 + \eta_7 \left( \frac{\partial \omega}{\partial p} \right)_7 - \eta_{10} \left( \frac{\partial \omega}{\partial p} \right)_{10} \quad (12)$$

However,

$$\left( \frac{\partial \omega}{\partial p} \right)_7 = \frac{(\omega_8 - \omega_6)}{\Delta p}, \quad (\omega_8 - \omega_6) = -\frac{1}{2} (a + b)$$

$$\left( \frac{\partial \omega}{\partial p} \right)_{10} = -\frac{b}{p_5}, \quad 2\Delta p = p_5$$

thus equation (12) becomes

$$g/f \nabla^2 \frac{\partial h_2}{\partial t} = \mathbf{V}_{10} \cdot \nabla \eta_{10} - \mathbf{V}_7 \cdot \nabla \eta_7 + \eta_{10} \frac{b}{p_5} - \eta_7 \left( \frac{a+b}{p_5} \right) \quad (13)$$

Substituting equations (7) and (9) into equation (13) and expressing advective terms in Jacobian form we obtain the following:

$$\nabla^2 \frac{\partial h_2}{\partial t} - \frac{16f}{7p_5 g} G \frac{\partial h_2}{\partial t} = J(D_{10}, \eta_{10}) - J(D_7, \eta_7) + \frac{16}{7p_5} G J(D_{10}, D_7) \quad (14)$$

$$\frac{16f}{7p_5 g} G \sigma_2 \omega_{10} + F J(D_5, \eta_5) + F \nabla^2 \frac{\partial z}{\partial t} - \frac{16f}{7g p_5} G \frac{R \Delta p}{g c_p p_8} \dot{Q}_2$$

where

$$\mathbf{V}_8 \cdot \nabla h_2 = g/f J(Z_{10}, Z_7) = g/f J(D_{10}, D_7), \quad \mathbf{V}_{10} \cdot \nabla \eta_{10} = J(D_{10}, \eta_{10})$$

and

$$F = \left( \frac{\eta_{10} + 3\eta_7}{7\eta_5} \right), \quad G = \left( \frac{\eta_7 - 2\eta_{10}}{\sigma_2} \right)$$

The prognostic thickness equation is thus determined for the lower layer. This equation is of the Helmholtz type, the solution of which may readily be obtained by use of a digital computer.

We will now obtain a prognostic equation for the thickness of the upper layer.

Evaluating equation (2) for the upper level centered at 625 mb results in the following:

$$\frac{\partial h_1}{\partial t} = -\mathbf{V}_6 \cdot \nabla h_1 - \sigma_1 \omega_6 + \frac{R \Delta p}{g c_p p_6} \dot{Q}_1 \quad (15)$$

where

$$\sigma_1 = \left( \frac{c_v}{c_p p_6} h_1 - \frac{(h_1 - h_2)}{\Delta p} \right)$$

Substituting from equations (4), (7) and (9) and simplifying, we obtain

$$\omega_6 = -\frac{15}{7\sigma_2} \mathbf{V}_8 \cdot \nabla h_2 - \frac{15}{7\sigma_2} \frac{\partial h_2}{\partial t} - \frac{3p_5}{14\eta_5} \left( \frac{\partial p_5}{\partial t} \right) - \frac{3p_5}{14\eta_5} (\mathbf{V}_5 \cdot \nabla \eta_5) \quad (16)$$

$$+ \frac{15}{7\sigma_2} \frac{R \Delta p}{g c_p p_8} \dot{Q}_2 - 8/7 \omega_{10}$$

Substitution of equation (16) into equation (15), and expressing in Jacobian form provides the thickness tendency (prognostic) equation for the upper layer of the model.

$$\frac{\partial h_1}{\partial t} = \frac{g}{f} J(D_s, D_1) + \frac{15 g \sigma_1}{7 f \sigma_2} J(D_{10}, D_1) + \frac{15 \sigma_1}{7 \sigma_2} \frac{\partial h_2}{\partial t} + \frac{3 \sigma_1 p_s g}{14 \eta_s f} \nabla^2 \frac{\partial z}{\partial t} \quad (17)$$

$$+ \frac{3 \sigma_1 p_s g}{14 \eta_s f} J(D_s, \eta_s) - \frac{15 \sigma_1 R \Delta p}{7 \sigma_2 g c_p p_b} \dot{Q}_2 - \frac{R \Delta p}{g c_p p_b} \dot{Q}_1 + \frac{8}{7} \sigma_1 w_{10}$$

where

$$\nabla \cdot \nabla h_1 = \frac{g}{f} J(D_1, D_s)$$

### III. Development of the heating term.

Initially it will be assumed that the heating rate is expressed by an equation of the following format

$$\dot{Q} = A f(V_s) (T_s - T_a) \left( \frac{p}{p_{10}} \right)^k \quad (18)$$

Over land the heating term is quite small, and we shall consider it as negligible. Over water, excluding radiation, the main contributions to the heating term are due to sensible and latent heat exchange between the sea and the atmosphere. It is of course realized that latent heat gained through evaporation may not be utilized by the atmosphere at the exact instant and position that it is obtained. However, in the relationship derived, an empirical adjustment constant is available should the values calculated be determined to be somewhat too small or large.

According to Laevastu [ 3 ] the heat flux from the ocean to the atmosphere due to sensible heat transfer and evaporation or condensation may be expressed as follows:

$$\dot{Q}_{FH} = \frac{39}{24} (0.26 + 0.77 V_s) (T_s - T_a) \left( \frac{\text{gm cal}}{\text{cm}^2 \text{ hr}} \right) \quad (19)$$

$$\dot{Q}_{FE} = \frac{L}{24} (0.26 + 0.77 V_s) (.98 e_s - e_a) \quad (20)$$

for  $(T_s - T_a) \geq 0$

$$\dot{Q}_{FH} = \frac{3 V_s}{24} (T_s - T_a) \quad (21)$$

$$\dot{Q}_{FC} = \frac{.077 V_s}{24} (e_s - e_a) L \quad (22)$$

for  $(T_s - T_a) < 0$

It is apparent that the contribution from the latter equation is small and hence will be considered zero.

By equating the relationship (19) given by Laevastu for sensible heat flux with the integral of equation (18) with respect to mass per unit area, we may determine a reasonable value for the constant "A".

Integrating (18) with respect to mass per unit area gives

$$\dot{Q}_F = \int_0^{z_s} A f(V_s) (T_s - T_a) \left( \frac{p}{p_0} \right)^2 \rho dz$$

where

$$k = 2$$

Introducing the hydrostatic relationship,  $\rho dz = -\frac{dp}{g}$  and integrating with respect to pressure, and then equating this term to the heat flux (19) yields



$$\frac{A f(V_s)(p_0^3 - p_s^3)(T_s - T_a)}{3 g p_0^a} = \frac{39}{24} (0.26 + 0.77 V_s)(T_s - T_a) \frac{(4.19 \times 10^7)}{3600} \left( \frac{\text{ergs}}{\text{cm}^2 \text{sec}} \right)$$

Solving this equation for A, and placing  $f(V_s) = (0.26 + 0.77 V_s)$  leads to a value of 63.5 for A. The resulting term for the sensible heat contribution becomes

$$\dot{Q}_H = 63.5 (0.26 + 0.77 V_s)(T_s - T_a) \left( \frac{p_s}{p_0} \right)^2 \left( \frac{\text{ergs}}{\text{cm}^2 \text{sec}} \right) \quad (23)$$

Furthermore, since the wind used in the prognostic model will be the geostrophic wind at 1000 mb which is about 130 to 140 percent greater than the surface wind, the constant 0.77 in equation (23) was reduced to 0.5. This constant may be refined to further enhance the accuracy of the forecast.

The final form for this term thus becomes

$$\dot{Q}_H = 63.5 (0.26 + 0.5 V_{g10})(T_s - T_a) \left( \frac{p_s}{p_0} \right)^2 \quad (24)$$

for  $(T_s - T_a) \geq 0$

Bowen (1926) related the convective transfer of sensible heat to evaporation by the following relationship

$$\frac{\dot{Q}_H}{\dot{Q}_E} = B = K \frac{(T_s - T_a) p_a}{(e_s - e_a) 1000} \quad (25)$$

A. H. Gordon [2] (1952) using meteorological data from British ocean weather ships in the North Atlantic related the mean

values of vapor pressure differences ( $e_s - e_a$ ) to individual whole degree temperature differences of ( $T_s - T_a$ ) for wind forces 0-3, 4-6 and greater than 6.

Roll [4] using this data computed the Bowen ratio from corresponding average temperatures and water vapor differences ( $T_a - T_s$ ), ( $e_s - e_a$ ) for wind forces Beaufort 4 and 8. Only a very slight increase in the Bowen ratio was observed for force 8 winds. The results of those computations are presented in Fig. 2.

The curve of Fig. 2 was statistically fitted using a linear rational transformation and solving for the Bowen ratio in terms of temperature difference ( $T_s - T_a$ ) with the following result:

$$\beta = \frac{\dot{Q}_H}{\dot{Q}_E} = \frac{.2(T_s - T_a)}{1 + .12(T_s - T_a)} \quad (26)$$

As was previously indicated, the diabatic heating term is to be comprised only of the two elements  $\dot{Q}_H$  and  $\dot{Q}_E$ , hence the use of relationship (26) enables us to eliminate the vapor pressure differences as a parameter in the forecast. Thus  $\dot{Q}$  (Total Diabatic Heating Rate) =  $\dot{Q}_H + \dot{Q}_E$

$$= \frac{1 + .32(T_s - T_a)}{.2(T_s - T_a)} \dot{Q}_H \quad (27)$$

The total heating rate determined from equations (24) and (27) is thus

$$\dot{Q} = 317.5 (1 + .32(T_s - T_a)) (.26 + .5V_{gs10}) \left( \frac{p_s}{p_{i0}} \right)^2 \quad (28)$$

From equations (2) and (18), the rate of change of thickness due to diabatic heating in the lower and upper layers, which will be termed  $Q_2$  and  $Q_1$  respectively, may be expressed as follows

$$Q_2 = \frac{R \Delta p}{g c_p p_b} \left( \frac{p_b}{p_o} \right)^2 A \delta(V_s) (T_s - T_a)$$

$$= 7/32 \frac{R}{g c_p} A \delta(V_s) (T_s - T_a) \quad (29)$$

$$Q_1 = 5/32 \frac{R}{g c_p} A \delta(V_s) (T_s - T_a) \quad (30)$$

or  $Q_1 = 5/7 Q_2 \quad (31)$

We have thus established a simplified distribution of the effects of the diabatic heating.

From equations (28) and (31) the rate of change of thickness due to diabatic heating in the lower layer is then

$$Q_2 = 7/12 Q$$

$$= 15.2 (1 + .32 (T_s - T_a)) (.26 + .5 V_{gs10}) \left( \frac{cm}{hr} \right) \quad (32)$$

for  $(T_s - T_a) \geq 0$

Similarly, it may be shown that

$$Q_2 = 0.27 (V_{gs10}) (T_s - T_a) \quad (33)$$

for  $(T_s - T_a) < 0$



In comparison with equation (32), it is apparent that the magnitude of the thickness change due to this term will be quite small. However, the constant .27 may be increased if this contribution is deemed too small.

#### IV. Development of the terrain pressure and friction term

According to Berkofski and Bertoni [1], the vertical velocity produced by terrain may be expressed as follows:

$$\omega_T = -\rho g V_T \cdot \nabla Z_T \quad (34)$$

Making the geostrophic assumption, and also assuming that the 1000-mb wind is valid for all levels of terrain, this relationship may be expressed as follows:

$$\omega_T = -\rho_{10} \frac{g^2}{f} J(D_{10}, Z_T) \quad (35)$$

It is apparent that this term may be somewhat small in cases of high terrain due to the fact that the geostrophic wind at 1000 mb is used rather than an integrated wind over the entire height of the terrain. However, in nature, the wind will normally tend partially to parallel the terrain contours, hence this reduction will somewhat compensate for this deficit.

It was originally intended to use a more refined function for terrain induced vertical velocities and to include the effects of friction. Time limitations however precluded any further work on this term.

It is felt that further expansion of this term or the inclusion of the terrain term now calculated by FNWF into the program will render some improvement to the prognosis.

#### V. Programming the Prognostic Equations for the Control Data 1604 Computer

The prognostic equations were put into finite-difference form and programmed for the Control Data 1604 computer used in conjunction with the FE880 Univac storage drum. The 1604 computer is a stored program, general purpose digital computer with a storage capacity of 32,768 words in two independent storage units. The FE880 storage drum is connected to the 1604 computer by a high speed channel which conveys information at a rate of 3,000,000 bits per second. The drum capacity is 256 blocks of 5,120 48 bit words per block.

The program was written in symbolic coded relocatable assembly program (SCRAP) for a 63 by 63 hemispheric grid, with one hourly time steps.

An option was written into the program to allow for equating the vertical velocity due to terrain and the heating term to zero in order to ascertain their respective effects on the prognosis.

The 750-mb layer is not considered a standard layer in the atmosphere, so no synoptic information is available for the initialization of the program. To account for this, the following equation developed from the thickness equation was derived.

$$D_{750} = D_{700} + h_{st775} - [58.78 (T_{850} - T_{700}) + 202 T_{700}] \quad (36)$$

where  $h_{st775}$  is the standard thickness of the layers 700 to 750 mb.

Once the initialization of the program is completed the 750 mb height may be computed using the forecast thickness for the upper level and FNWF's 500-mb barotropic prognosis.

The absolute vorticities ( $\eta_s, \eta_7, \eta_{10}$ ) are computed with FNWF's subroutine SAR. This routine computes the absolute vorticity over a 63 by 63 grid using the following relationships

$$\eta = a_1 \sin \phi + a_2 \frac{(A_1 + A_2 + A_3 + A_4 - 4A_0)}{\sin \phi}$$

Where  $a_1 = .0746711$

$a_2 = .2704348$

To use this routine, all data must be scaled  $2^{-17}$ . The absolute vorticity is equated to zero for all points south of 10 N latitude.

After computing the absolute vorticities and reading in the various D fields, the Jacobians may be computed utilizing Fleet Numerical Weather Facility standard subroutine SAB. The subroutine computes the Jacobian in the following manner

$$\begin{aligned} A &= J(B, C) \\ &= (\Delta_x B)(\Delta_y C) - (\Delta_y B)(\Delta_x C) \end{aligned}$$

The program inserts zeroes in field A at the boundaries.

The next term computed is the  $\nabla^2 \Delta D_5$ . This term is computed by Fleet Numerical Weather Facility's subroutine SAD, which computes as follows:

$$A = \nabla^2 B$$

$$= B_{i+1,j} + B_{i-1,j} + B_{i,j+1} + B_{i,j-1} - 4B_{i,j}$$

This program also zeroes the field at the boundaries.

To compute the heating term,  $Q_2$  we must obtain an hourly surface temperature based on the forecast thickness and also compute a 1000-mb geostrophic wind. The sea surface temperature was assumed to remain constant throughout the period of the forecast.

The equation developed to determine an hourly surface temperature as derived from the predicted thickness fields is as follows:

$$T_{sfc} = 3.415 \times 10^{-4} \left[ (10.33 h_2 - 7.33 h_1) \ln \left( \frac{8.11 \times 10^5 + D_{10}}{5 \times 10^6} \right) + 2.47 h_1 \right] \quad (37)$$

After  $Q_2$  is calculated, each point in the grid is checked to determine whether it is a land or sea point. At land points  $Q_2$  is equated to zero; at sea points, as calculated.

The terrain term  $w_{10}$  is computed using the Jacobian subroutine and also checked against the land/sea table. In this case, sea points are zeroed and land points left unchanged.

The terms now calculated are collected and make up the forcing function for the Helmholtz equation (14). This equation is solved using FNWF's subroutine SAE, providing  $\Delta h_2$  for the first hour of the prognosis.

To solve the Helmholtz equation,  $\nabla^2 A - BA = C$ , the program scans through field A laterally from the lower left point to the upper right point using the extrapolated Liebmann method of computing a new point value. The boundary conditions have already been determined and stored in the A field, the guess field, which is originally set to zero.

$$A_{i,j}^{x+1} = A_{i,j}^x + \frac{\lambda}{4} \left[ \frac{\nabla^2 A_{i,j} - (AB)_{i,j} - C_{i,j}}{2^{-2} B_{i,j} + 1} \right]^x$$

$$R_{i,j}^x = \frac{\lambda}{4} \left[ \frac{\nabla^2 A_{i,j} - (AB)_{i,j} - C_{i,j}}{2^{-2} B_{i,j} + 1} \right]^x$$

When for all points  $|R_{i,j}| \leq \epsilon$  where  $\epsilon$  is the criterion for convergence or the point where the residual R is considered liquidated, the field is assumed relaxed and a proper solution has been obtained at each grid point.

When  $\Delta h_2$  has been determined, all the parameters required for the computation of  $\Delta h_1$  are available for use in equation (17).

The change in height at 1000 mb is then determined by subtraction of  $\Delta h_1$  plus  $\Delta h_2$  from the 500-mb height change as computed by the FNWF barotropic model.



## 6. Results and Conclusions

Twenty four hour thickness forecasts were produced from initial data on 20, 23 and 29 May 1966. The initial program contained a number of smoothing passes at many stages of the prediction procedure. As a result the initial thickness prognosis was very smooth, almost zonal, as shown in Figure 4. Comparison of this prognosis with the initial and verifying maps, Figures 3 and 6, clearly shows that oversmoothing was a major source of error. In figures 5, 10 and 13 for the 20th, 23rd and 29th of May the results were slightly more encouraging. Here smoothing has been reduced somewhat and lower limits were placed on absolute vorticity and stability. Still further elimination of smoothing throughout the prediction procedure gave the thickness and 1000-mb prognosis for the 29th in Figures 15 and 19, which show genuine promise as a useable forecast. No 1000-mb analysis existed for the 21st and 24th.

Generally, the pressure systems moved realistically and the final positions were good. However, some excess movement was observed which might be partially attributed to the smoothing still remaining in the model. Some overdevelopment of both high and low pressure systems in Figure 15 was also observed. However FNWF has a filtering subroutine which in addition to filtering out the ultra short waves reduces the amplitude of these centers. This subroutine diminishes the effect of simply spreading the patterns to adjacent grid points

which is inherent in smoothing subroutines. Smoothing can also give rise to fictitious movement of pressure systems.

By replacing the smoothing with a filtering pass some of the difficulties of excess movement and overdevelopment could be overcome.

Another problem is the tendency of some thermal systems, known for their persistence, to move with the general circulation, an example is the heat low in Southwestern United States. Periodic comparison with climatology could be fruitful in reducing this tendency.

Due to a lack of available computer time little consideration could be given to the diabatic heating and terrain terms. Further refinement and inclusion of these terms could result in some improvement of the prognosis.

The program running time on the 1604 computer for a 24-hour forecast was about 30 minutes, including hourly writing on magnetic tape of a number of fields which would be unnecessary in an operational model.

The FNWF thickness forecast in Figure 16, which is based on simple horizontal advection and numerous constraints, is obviously superior to the prognosis resulting from the model under investigation.... However, the superiority is a result of several years of refinement and empirical adjustment. Time did not permit such thorough investigation of this research model.

In conclusion, it has been determined that the assumptions

used in the construction of this model are reasonable. With proper adjustment and refinement this model should yield a good forecast of thickness. This, in turn, should produce a good surface prognosis.



## ACKNOWLEDGEMENTS

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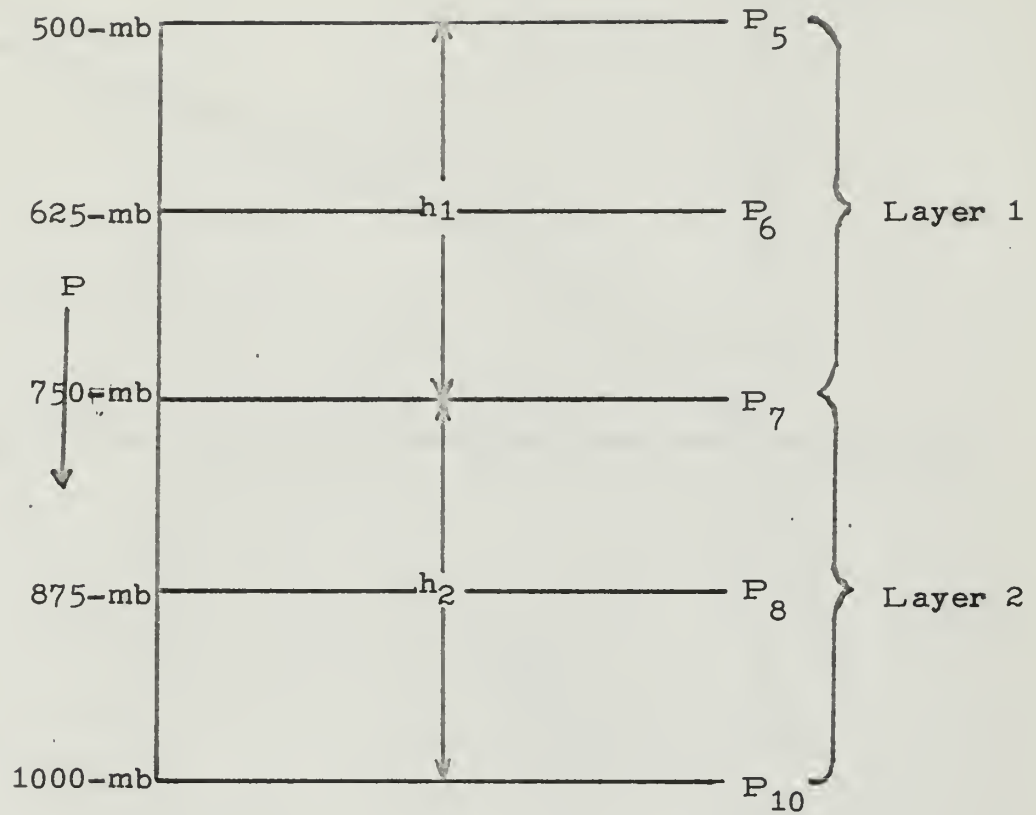


Figure 1. Two Layer division of the atmosphere between 1000-mb and 500-mb.  $h_1$  and  $h_2$  are the thickness of the layers  $p_1$  to  $p_5$  and  $p_{10}$  to  $p_7$  respectively.

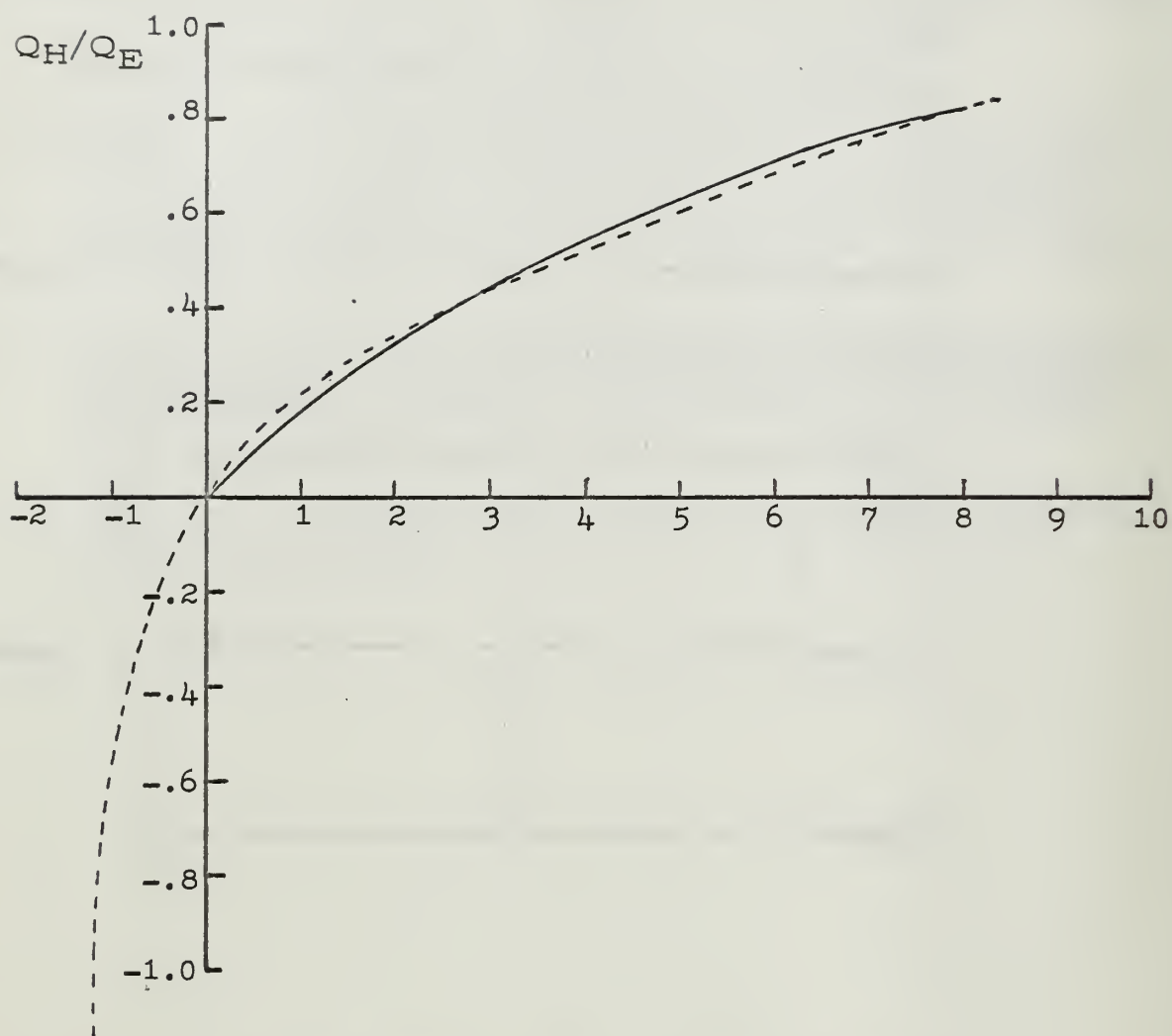


Figure 2. Bowen Ratio vs. Sea-Air Temperature Difference  
(dashed curve)

Linear rational transformation for positive values,  
Equation (26) (Solid curve).





THICKNESS 24 HR PROG FROM 00Z 20 MAY 66

FIGURE 4

PROJECTION POLAR STEREOGRAPHIC—TRUE AT 60° NORTH LATITUDE  
SCALE 1:60,000,000

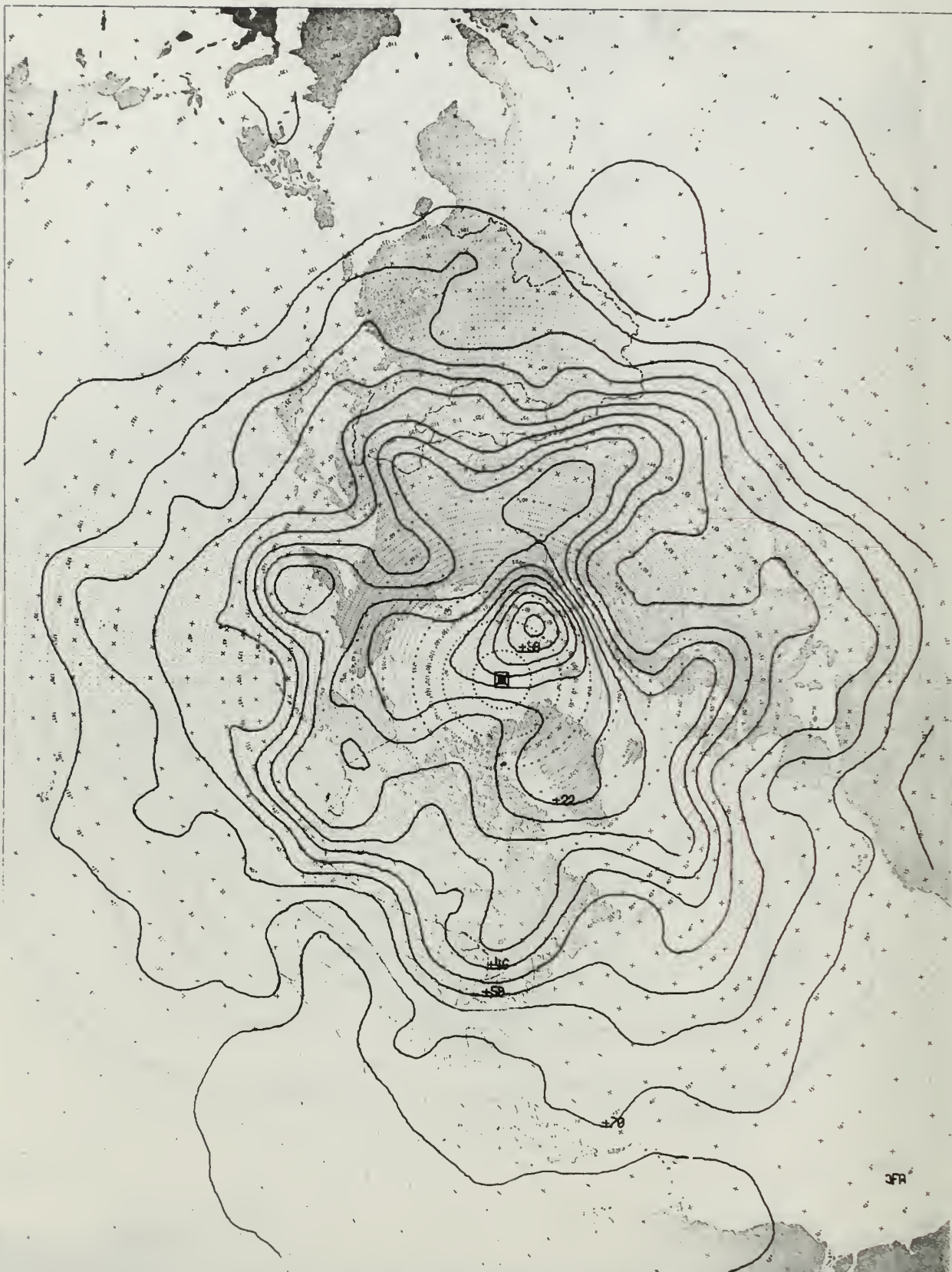
34

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H 5-10 ANAL 00Z 21 MAY 66

FIGURE 6

PROJECTION POLAR STEREOGRAPHIC - TRUE AT 60° NORTH LATITUDE  
SCALE 1:60 000 000

36

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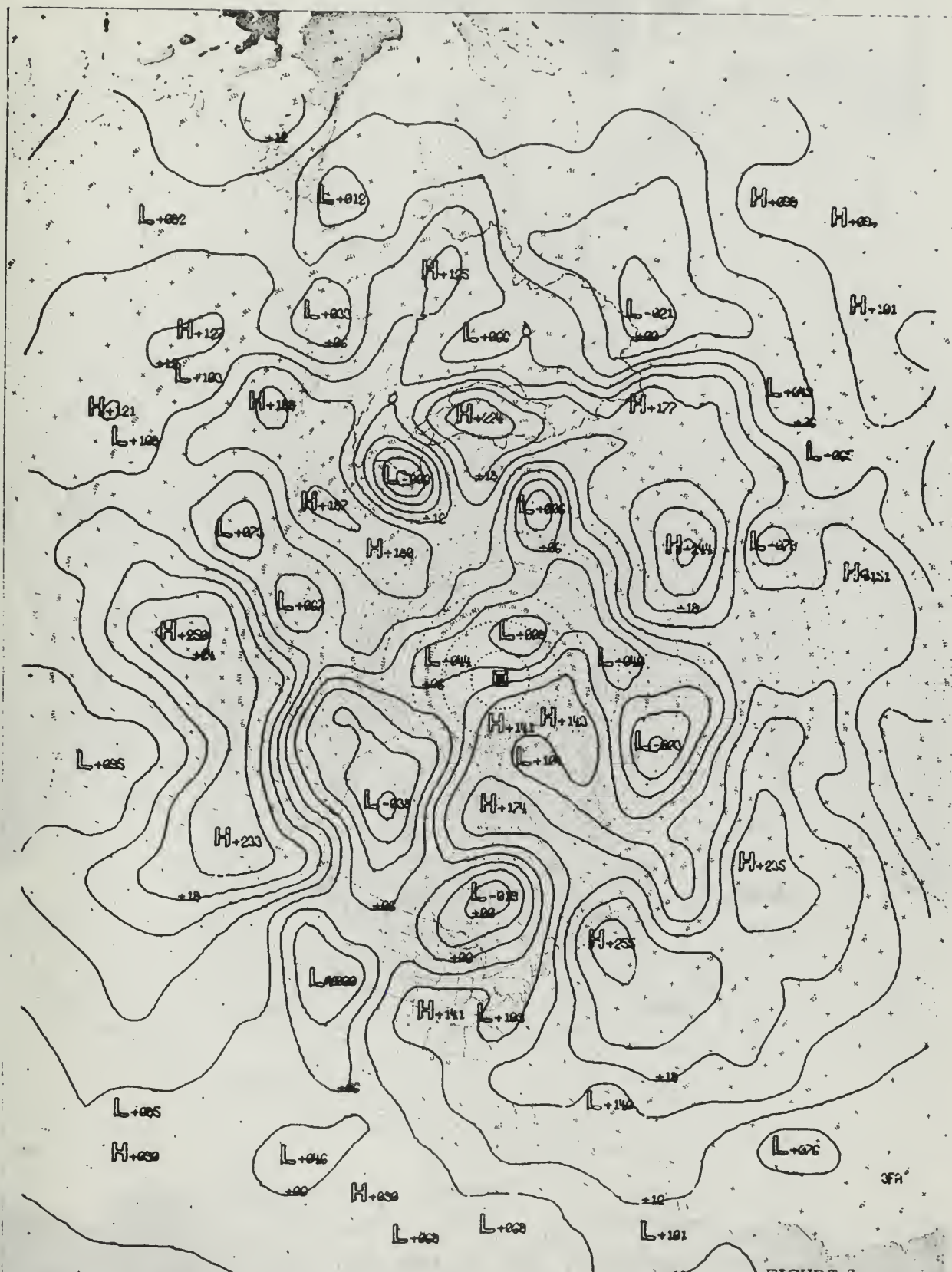


FIGURE 7

1000 HT ANAL

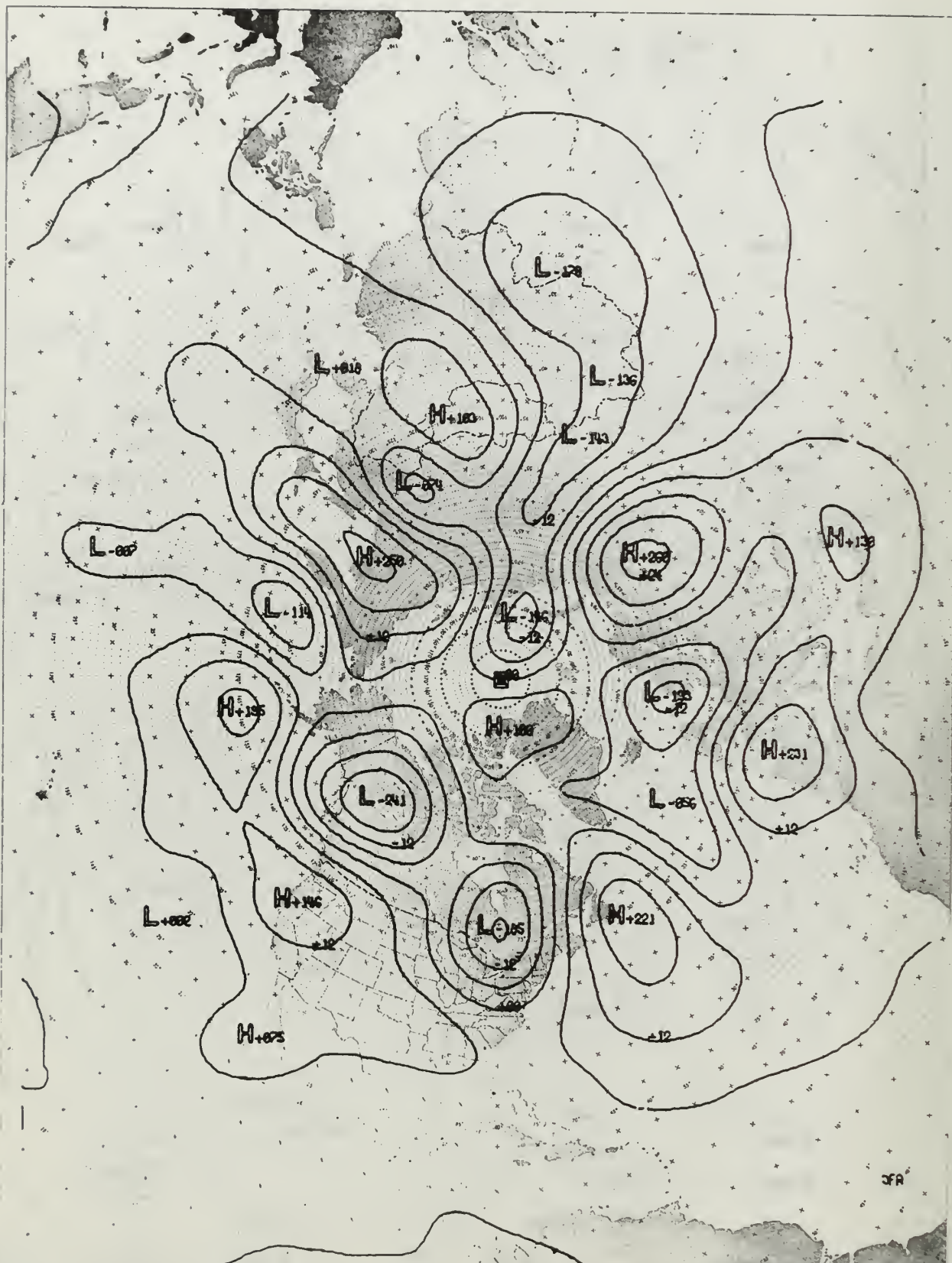
00Z 20 MAY 66 MB HEIGHT FIELD D VALUES

PROJECTION: POLAR STEREOGRAPHIC TRUE AT 60 NORTH LATITUDE  
SCALE 1:60,000,000

37

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1000 HT, 24 HR PROG FROM 00Z 20 MAY 66

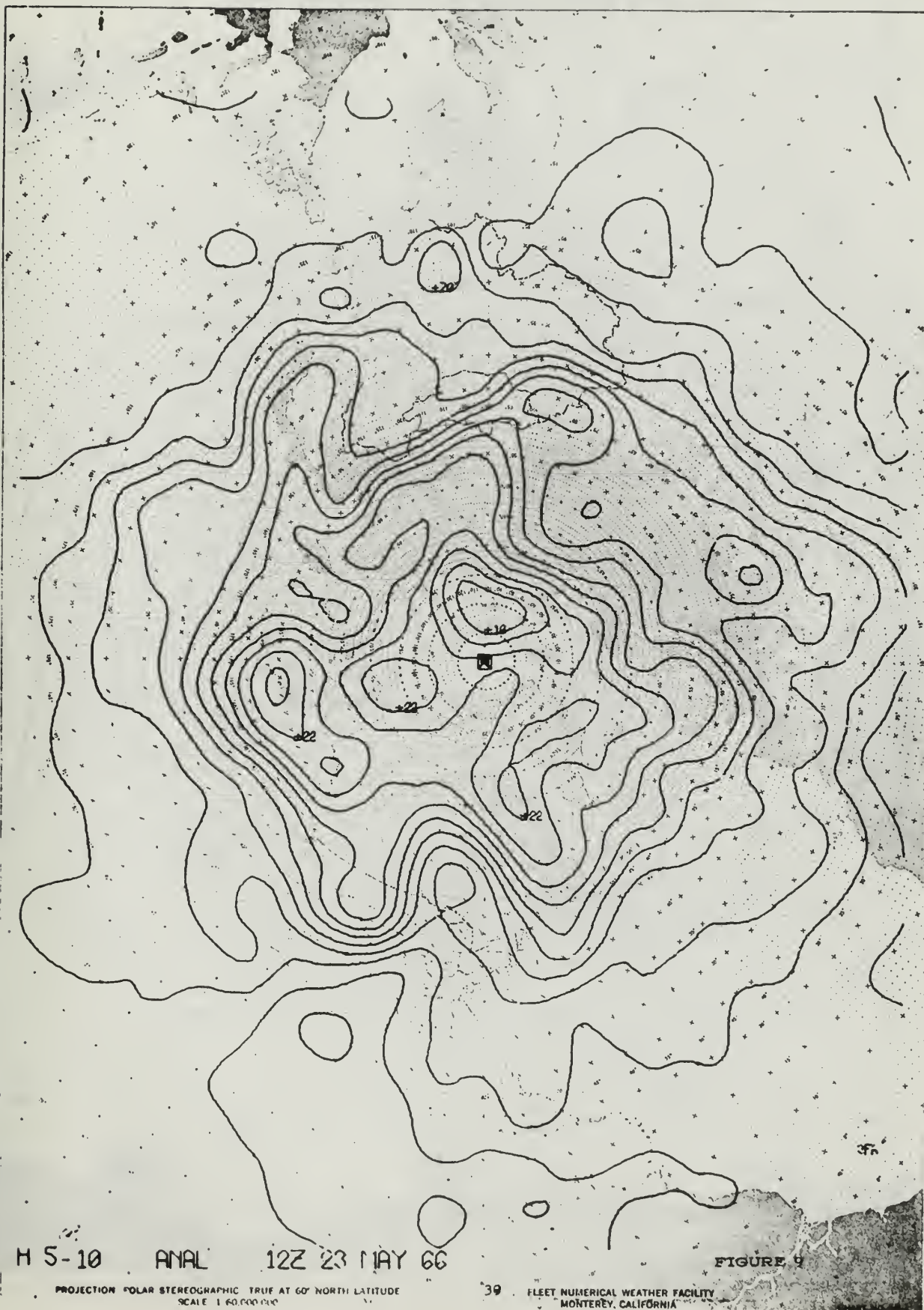
FIGURE 8

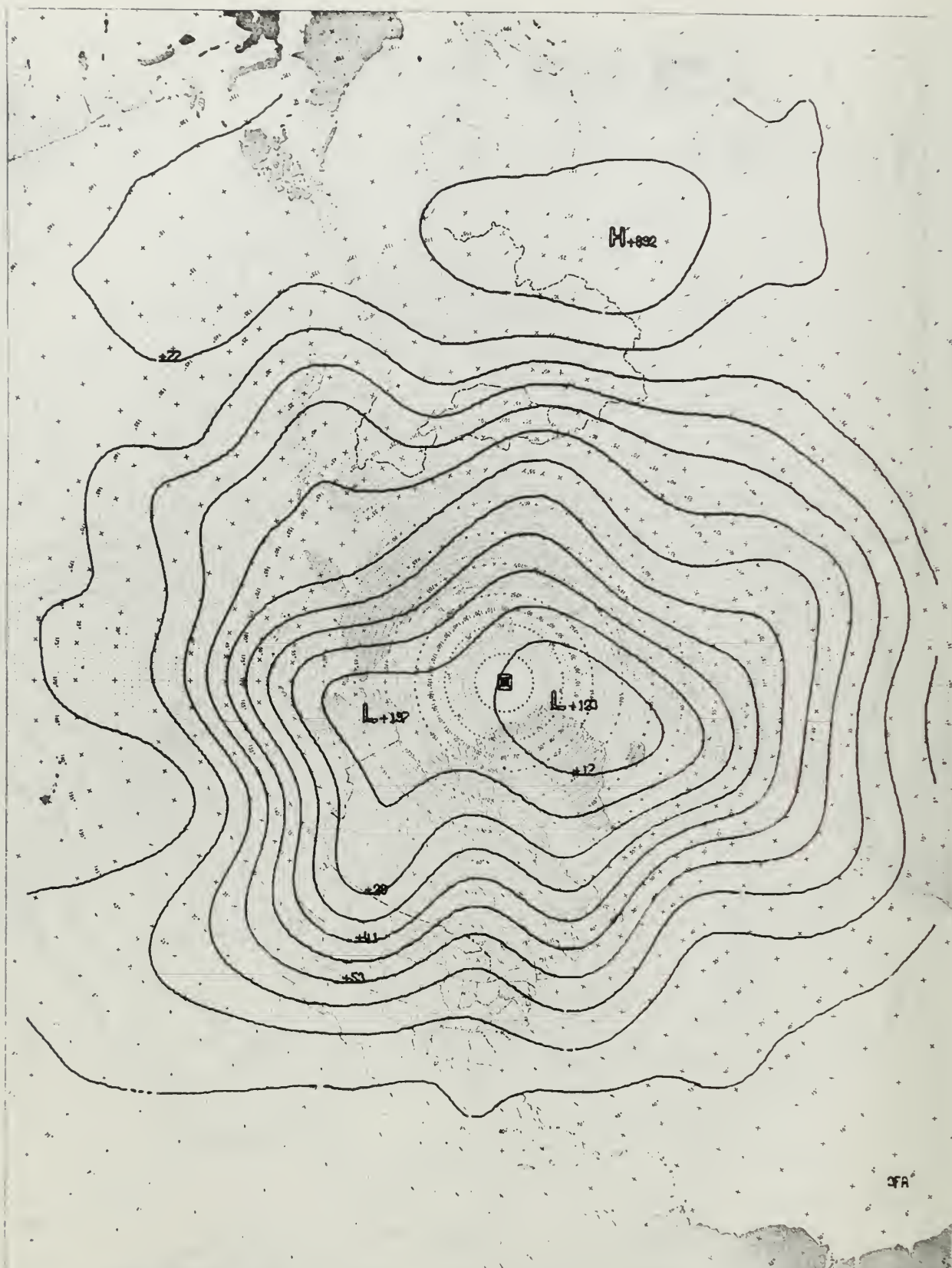
PROJECTION POLAR STEREOGRAPHIC TRUE AT 60 NORTH LATITUDE  
SCALE 1:60,000,000

38 FLEET NUMERICAL WEATHER FACILITY  
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Chart No. 66-1







THICKNESS 24 HR PROG FROM 12Z 23 MAY 66

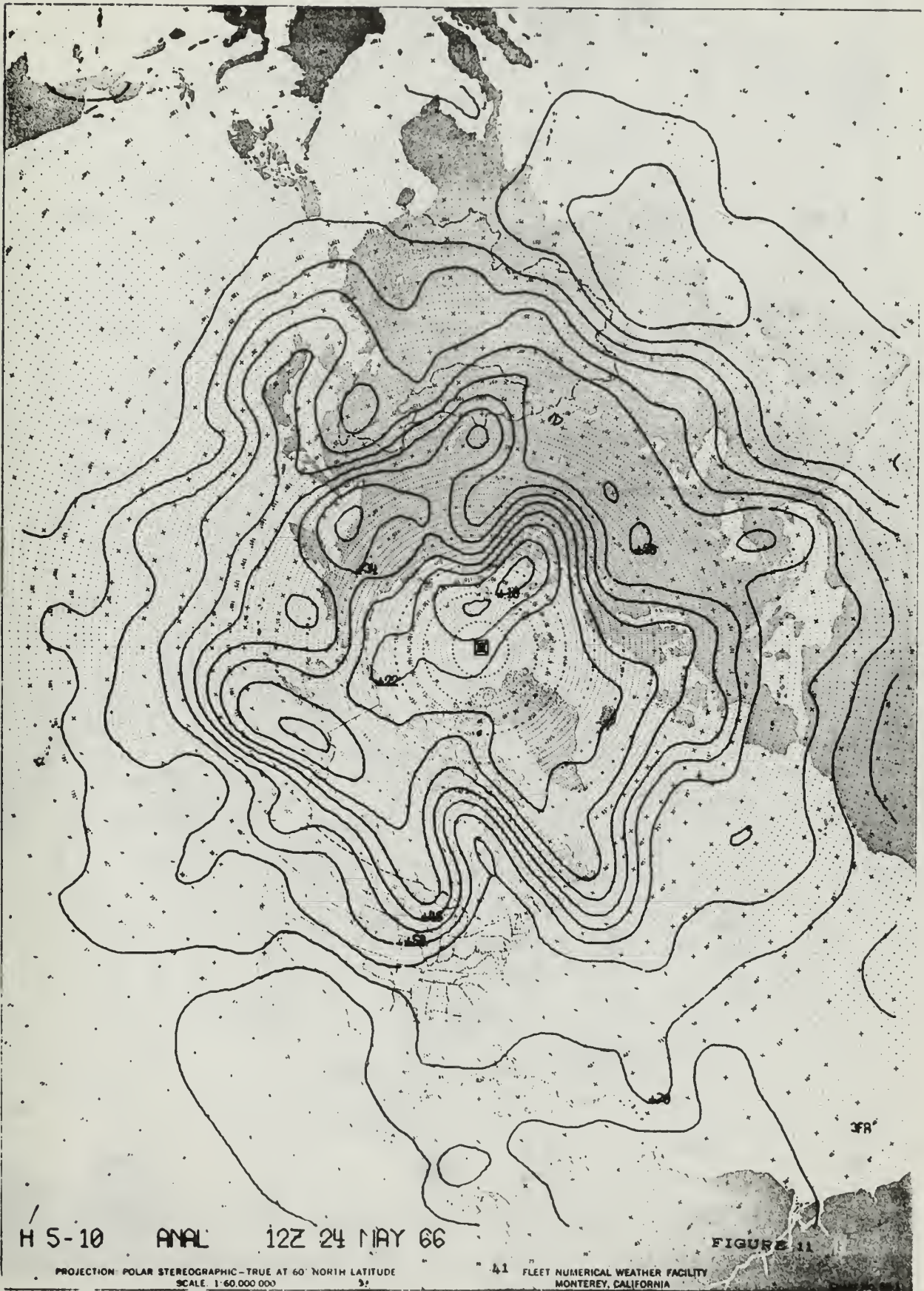
FIGURE 10

PROJECTION POLAR STEREOGRAPHIC - TRUE AT 60° NORTH LATITUDE  
SCALE 1:60 000 000

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H 5-10

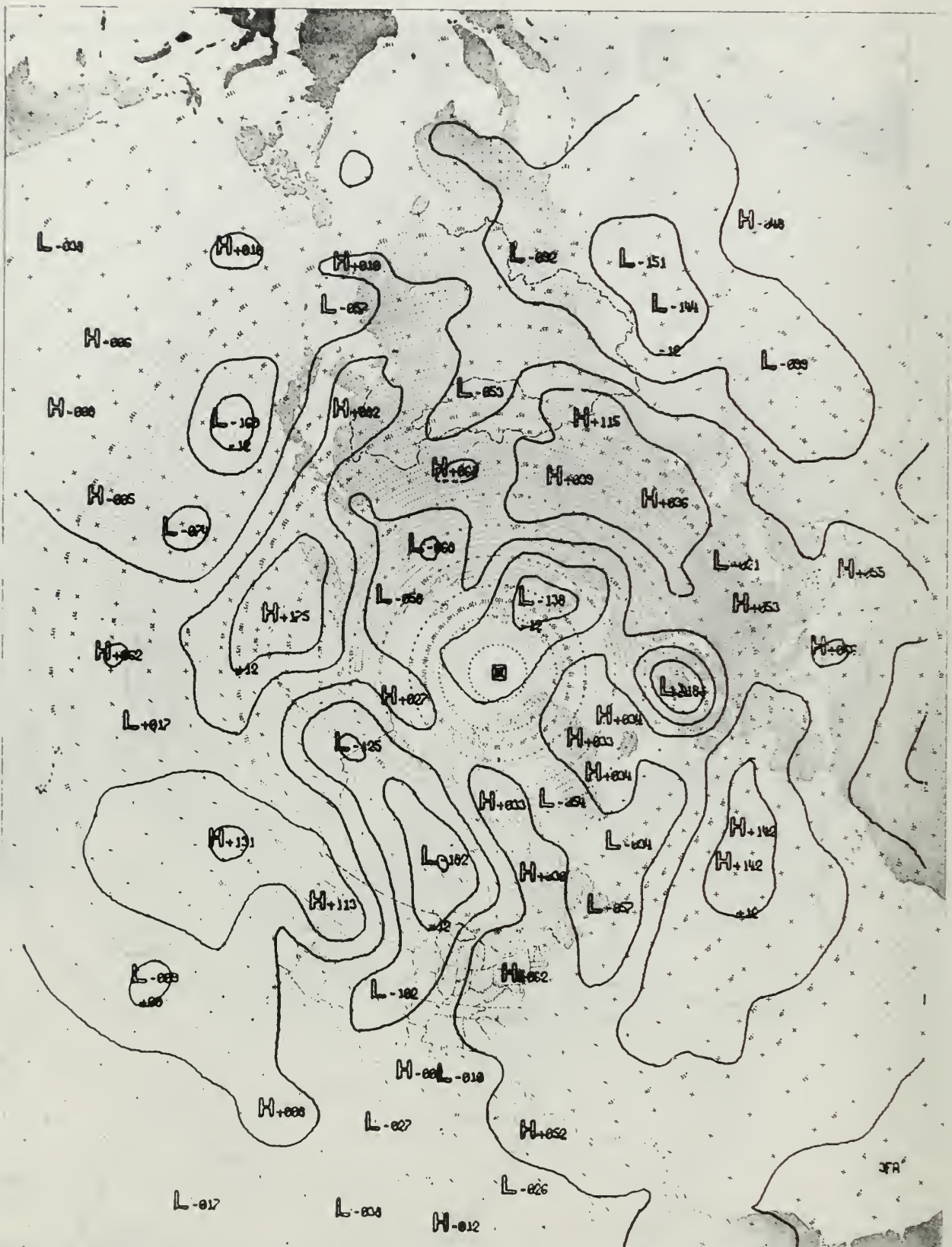
ANAL

12Z 24 MAY 66

FIGURE 11

PROJECTION: POLAR STEREOGRAPHIC - TRUE AT 60° NORTH LATITUDE  
SCALE: 1:60,000,000

41 FLEET NUMERICAL WEATHER FACILITY  
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1000 HT ANAL

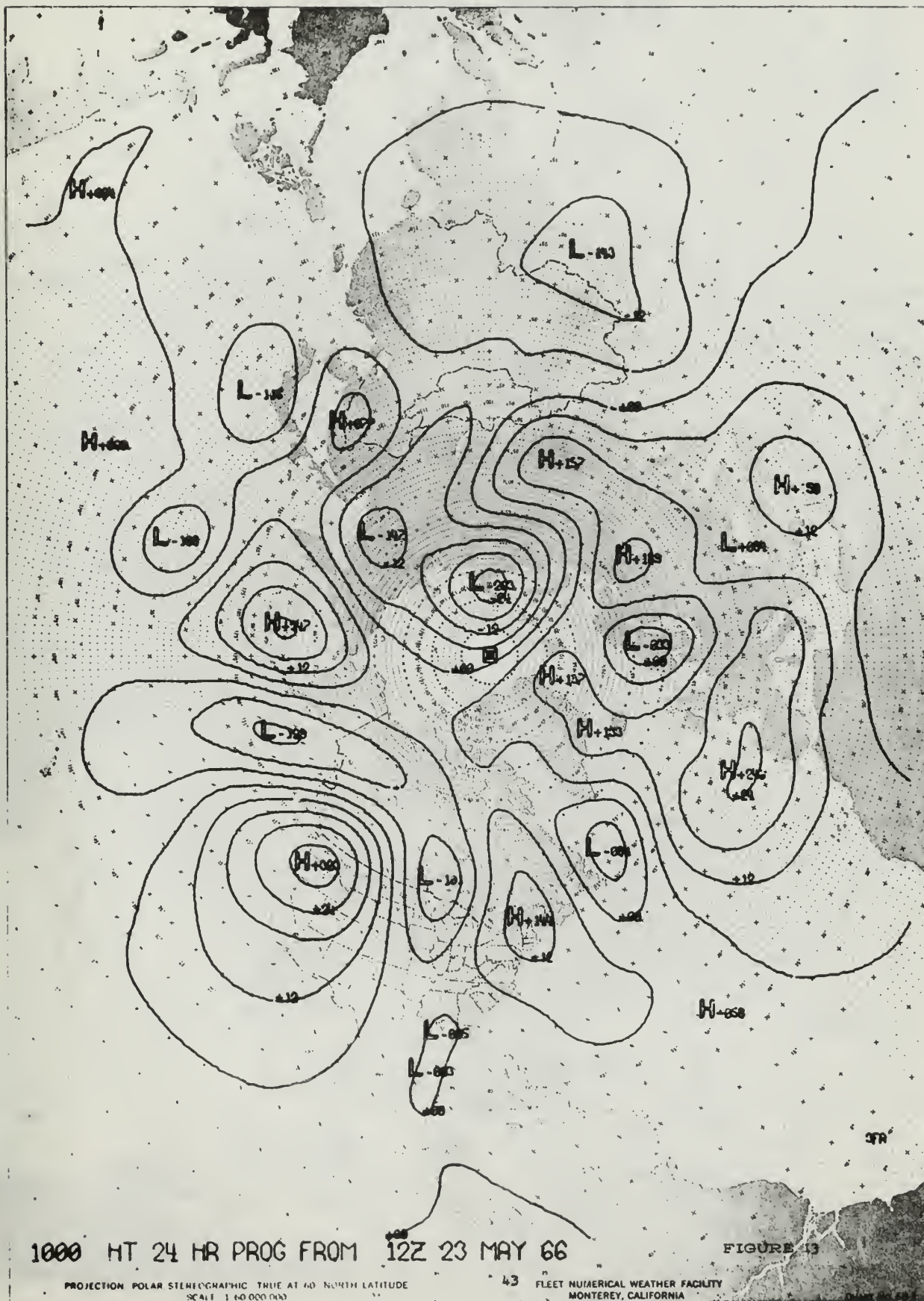
12Z 23 MAY 66 MB HEIGHT FIELD D VALUES

PROJECTION POLAR STEREOGRAPHIC TRUE AT 60° NORTH LATITUDE  
SCALE 1:60,000,000

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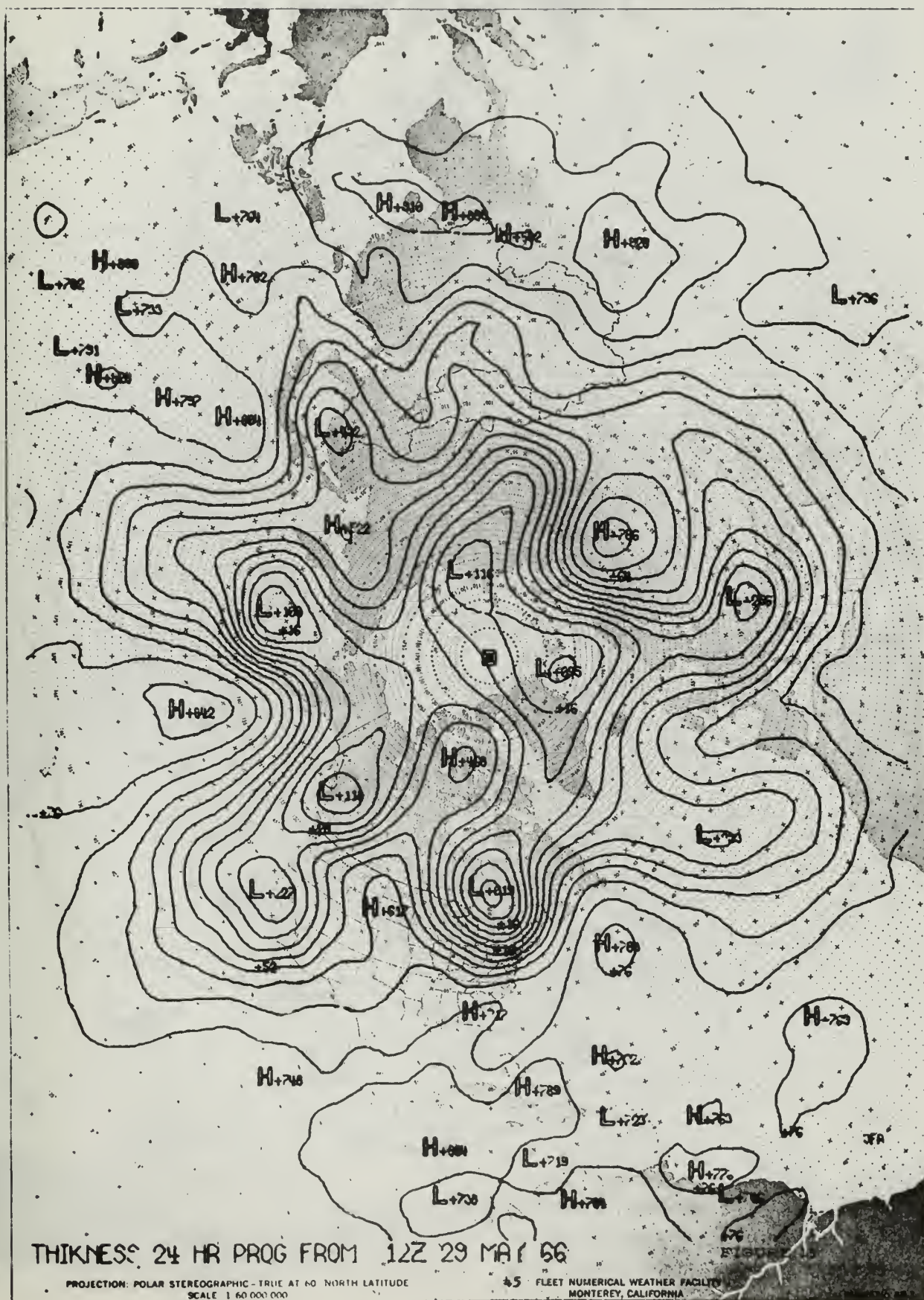
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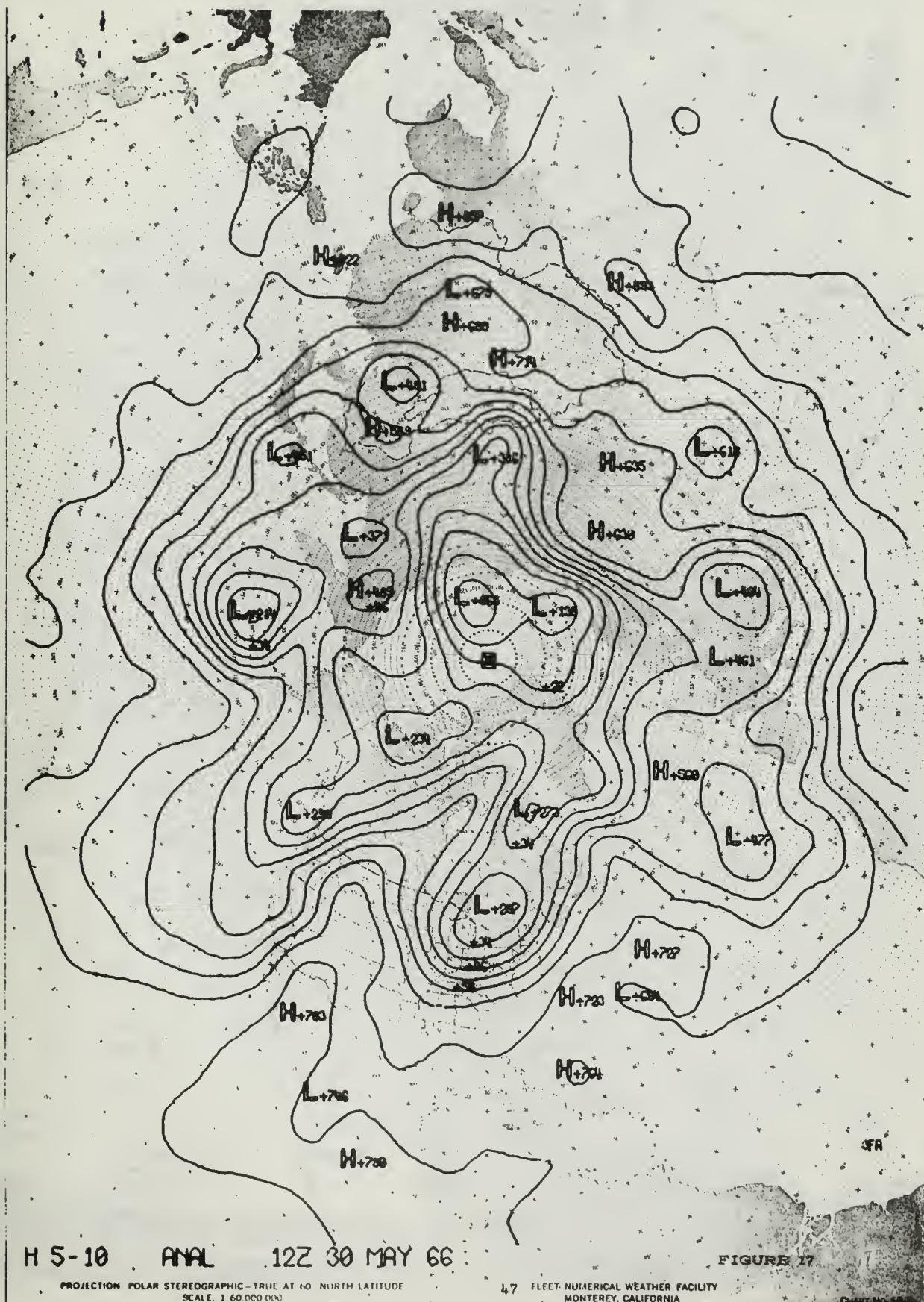






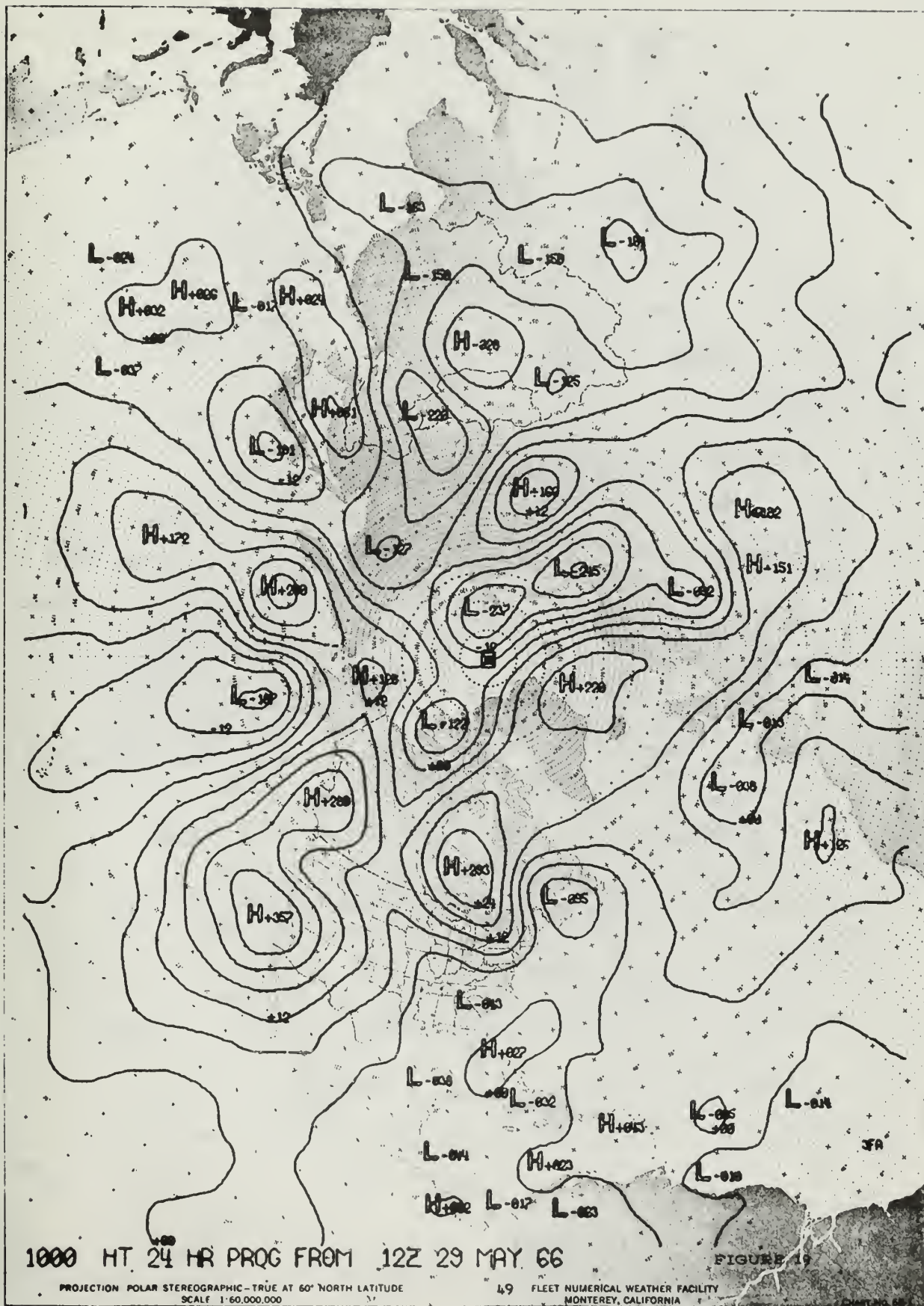








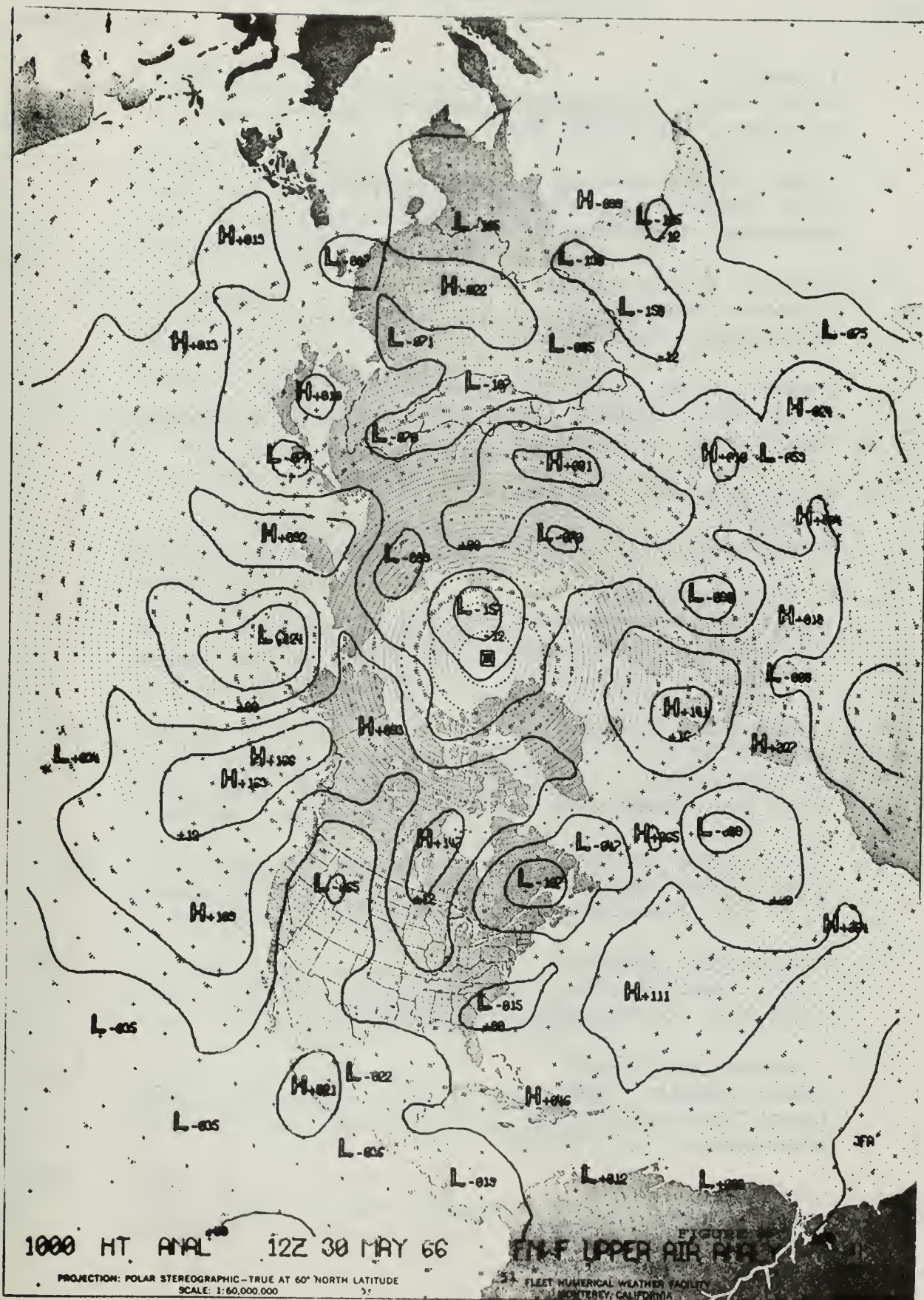












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The development of a numerical 1000-mb prognosis by means of a 500 to 1000-mb thickness forecast is investigated. The thickness forecast is based, in part, on the 500-mb barotropic prognosis as developed by Fleet Numerical Weather Facility, Monterey.

Forecasts were prepared for three days during May 1966, with various amounts of smoothing of the component fields. The model showed promise of producing a rapid, usable prognosis; however further testing is needed with the probable addition of some climatic constraints. It is also hoped that the yet untried diabatic heating and surface friction terms will provide some further improvement.

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